Soils and Agriculture of the Palau Islands[1]

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SOILS OF THE PALAU ISLANDS range from deeply weathered Latosols[3] to shallow, rocky Lithosols, and include Regosols, Alluvial Soils, and Organic Soils. Most extensive in the islands are the Latosols, of general interest because of their wide distribution in the humid tropics. Associated soils are much less extensive but are more important to local food production. The latter also illustrate effects of local factors in soil formation. Data on characteristics, distribution, and utilization of the soils and a preliminary evaluation of their agricultural potentialities are given in this paper. More complete descriptions of the soils are part of a comprehensive report on the geology and soils of the islands now being prepared for publication as a professional paper of the U. S. Geological Survey.

GEOGRAPHIC SETTING

Location and Extent

Most western group of the Caroline Islands, the Palau chain is almost directly south of Tokyo and due east of Mindanao. Location of the group in the western Pacific Ocean is shown in Figure 1. Lying 7° north of the equator, the Palaus are in the same latitude as Colombia and Venezuela.

The Palau chain stretches approximately 50 miles, from Kayangel at the north to Angaur at the south. From east to west, the dimensions of the chain range from 3 to 25 miles, as measured to the outer barrier reefs.

The total land area of the group, which consists of some 350 closely spaced islands and islets, is 175 square miles. Babelthuap, largest island in the group, has an area of almost 140 square miles. The bulk of the remaining land area is distributed among eight additional islands. Most of the 350 islands and islets of the chain are tiny reefs or bars, barely above sea level.

Physiography and Topography

The four types of islands in the Palau group are reef and atoll islands, platform islands, high limestone islands, and volcanic islands (Tayama, 1953). The reef and atoll islands, by far the most numerous, are flat land surfaces only a few feet above sea level. Examples of this type are Kayangel atoll at the north end of the chain and the many small unnamed reefs and atolls north of Peleliu. The platform islands, also mainly flat, are a little higher than the reefs and atolls. Angaur and Peleliu are chiefly of this type, though part of each consists of limestone ridges. The high limestone islands rise steeply out of the sea and are mostly narrow and elongated in shape. A few have the form of mushrooms. The principal high limestone islands are Urukthapel and Eil Malk; these and the numerous small ones all lie between Koror and Peleliu, approximately 25 miles apart. Parts of

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[1] A reconnaissance soil survey of the islands was made in 1948 as a part of a cooperative program of soil and geological mapping of islands in the western Pacific Ocean carried out cooperatively by the Corps of Engineers, U. S. Army, and U. S. Geological Survey, Department of the Interior. Manuscript received June 12, 1957.

[2] Soil Scientists, Soil Survey, Soil Conservation Service, U. S. Department of Agriculture. The authors were on assignment to the U. S. Geological Survey and the Corps of Engineers for the mapping of the Palau Islands.

[3] Latosol is a term proposed within the past few years to include zonal soils formerly called Laterites, Reddish-Brown Lateritic soils, and Yellowish-Brown Lateritic soils (Kellogg, 1949).

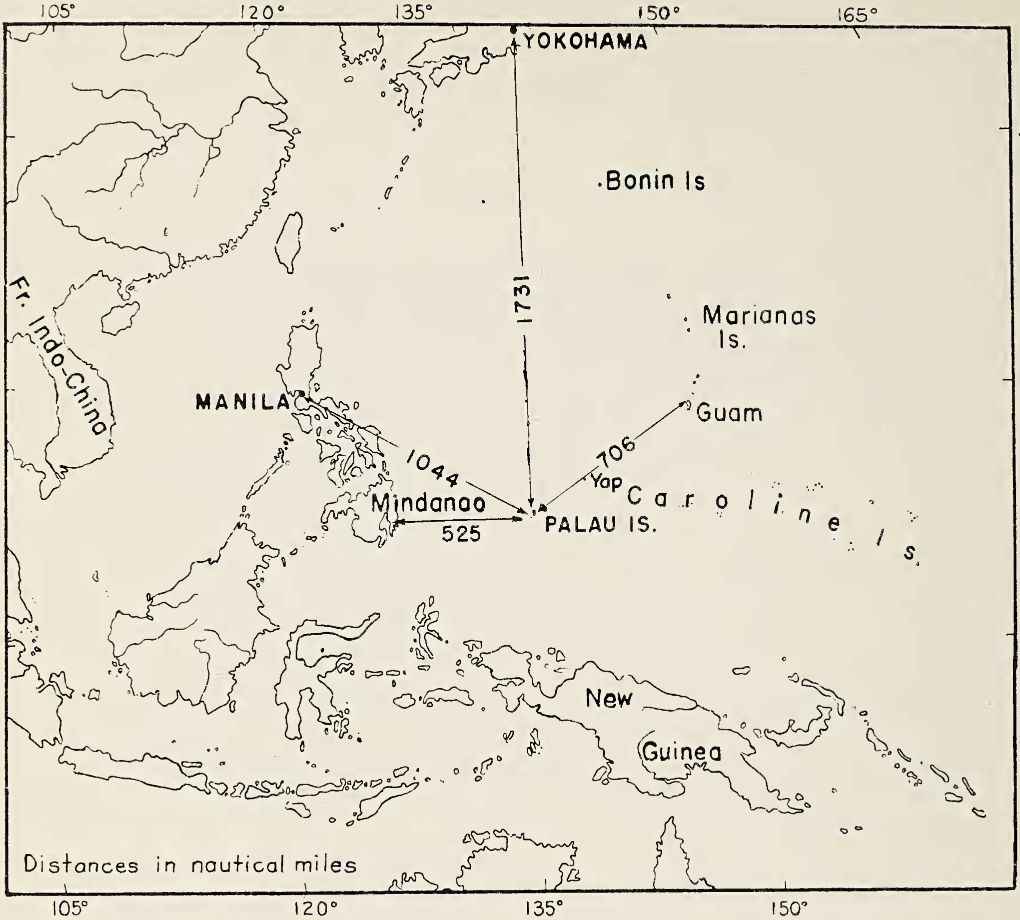

FIG. 1. Map showing the location of the Palau Islands in the western Pacific Ocean.

Peleliu, Angaur, and Koror and much of Auluptagel are also high limestone ridges. The maximum elevation of the high limestone islands is 686 feet above sea level on Urukthapel. Slopes of these islands are generally steep or very steep though a few have small central depressions with mild relief.

The volcanic islands, so named because of the underlying basement rock, are generally hilly to rolling with local relief commonly measurable in tens of feet. Slopes and ridge crests are rounded and subdued. Babelthuap has three prominent ridges running roughly parallel to the long north-south axis of the island. The highest elevation in the Palau Islands is that of 794 feet above sea level on one of the ridges in northwestern Babelthuap. The volcanic islands (Babelthuap, Arakabesan, Malakal, Auluptagel, and Koror) are all closely grouped in the northern part of the chain. As mentioned earlier, Auluptagel and Koror are partly volcanic rock and partly limestone.

Soil Parent Materials

The variety of rocks from which soils have been derived is relatively small in the Palaus. The platform and high limestone islands consist of former coral reefs. The present surface of the high limestone islands is largely a mass of rubble of assorted sizes. Much of the land surface of the platform islands also consists of rubble, commonly small in size. The principal volcanic rocks range from olivine-augite basalts to silicic hornblende dacites (Corwin, 1951) identified as andesitic agglomerates by Japanese geologists (Tayama, 1953) and also known as basaltic and andesitic volcanic breccias. Associated with the flow rocks and agglomerates on Babelthuap are some basic volcanic tuffs. Interbedded sedimentary clays and lignite comprise the surface formations in a few places in western and southeastern Babelthuap.

The distribution of rocks on the Palau Islands is strongly reflected in the distribution of soils (Fig. 2). Rocks of volcanic origin are parent materials for most of the Latosols. Some latosolic soils have also been formed from interbedded sedimentary clays. Deep soils with distinct horizons have not been formed from limestones, most of which have rubble surfaces. Where the volcanic rocks are exposed on steep or moderately steep slopes, shallow rocky Lithosols have been formed. Deep unconsolidated materials of recent origin have given rise to Regosols, Alluvial Soils, and Organic Soils.

Climate

Typical of the humid tropics, the islands have heavy annual rainfall and high mean temperatures with small seasonal differences (U. S. Dept. of Commerce, 1953). The islands also have rather steady winds, lying as they do in the trade-wind belt. The mean annual precipitation is 148 inches, with a maximum of about 19 inches in July and a minimum of nearly 8 inches in March. On the average, at least 15 days of each month have 0.04 inch or more of rain, whereas 7 days in July have 1 inch or more. The average relative humidity is 82 per cent, with a low of 79 per cent in March and a high of 83 per cent in July, November, and December. The mean annual temperature is 81° F. The maximum and minimum mean monthly temperatures are but one degree higher and lower, whereas the diurnal variation is about ten degrees. Prevailing winds are from the northeast and east from November to June and from the south and southwest for the remainder of the year.

Vegetation

The native vegetation (Fosberg, 1946) in the Palau Islands was rain forest, which remains in only a few places on Babelthuap. The rain forest consists of large trees, including *Parinarium*, *Campnosperma*, *Couthovia*, *Cynometra*, *Dysoxylum*, *Ficus*, *Semecarpus*, *Randia*, *Fagraea*, *Pittosporum*, *Schefflera*, *Horsfieldia*, and many others. Growing also in the rain forest are such palms as *Pseudopinanga* and *Exorrhiza;* an occasional slender *Pandanus;* such climbers as *Freycinetia*, *Canavalia*, *Piper*, aroids, and *Ipomoea;* also ferns, orchids, and other epiphytes. On both the low and high limestone islands, vegetative cover consists mainly of small to medium-sized trees and shrubs because moisture conditions are unfavorable for plant growth.

The most extensive vegetative type today is anthropic savanna consisting of coarse grasses, weeds, and occasional shrubs. Common genera in the savanna are *Ischaemum*, *Paspalum*, *Digitaria*, *Miscanthus*, *Lycopodium*, *Nepenthes*, and *Pandanus* (Fosberg, 1946). Soils of extremely low fertility support almost pure stands of a fern, *Gleichenia linearis*.

SOILS

The general character and distribution of soils were determined through a reconnaissance survey, according to procedures already described (Simonson, 1953; Soil Survey Staff, 1951). This reconnaissance survey was part of a program of soil and geologic investigations in the western Pacific Ocean (Simonson, 1953). How the soils were being used was observed during the field mapping from March through August, 1948.

Distribution of the soils and land types of the islands is shown in Figure 2. The map units are either soil associations or miscel-

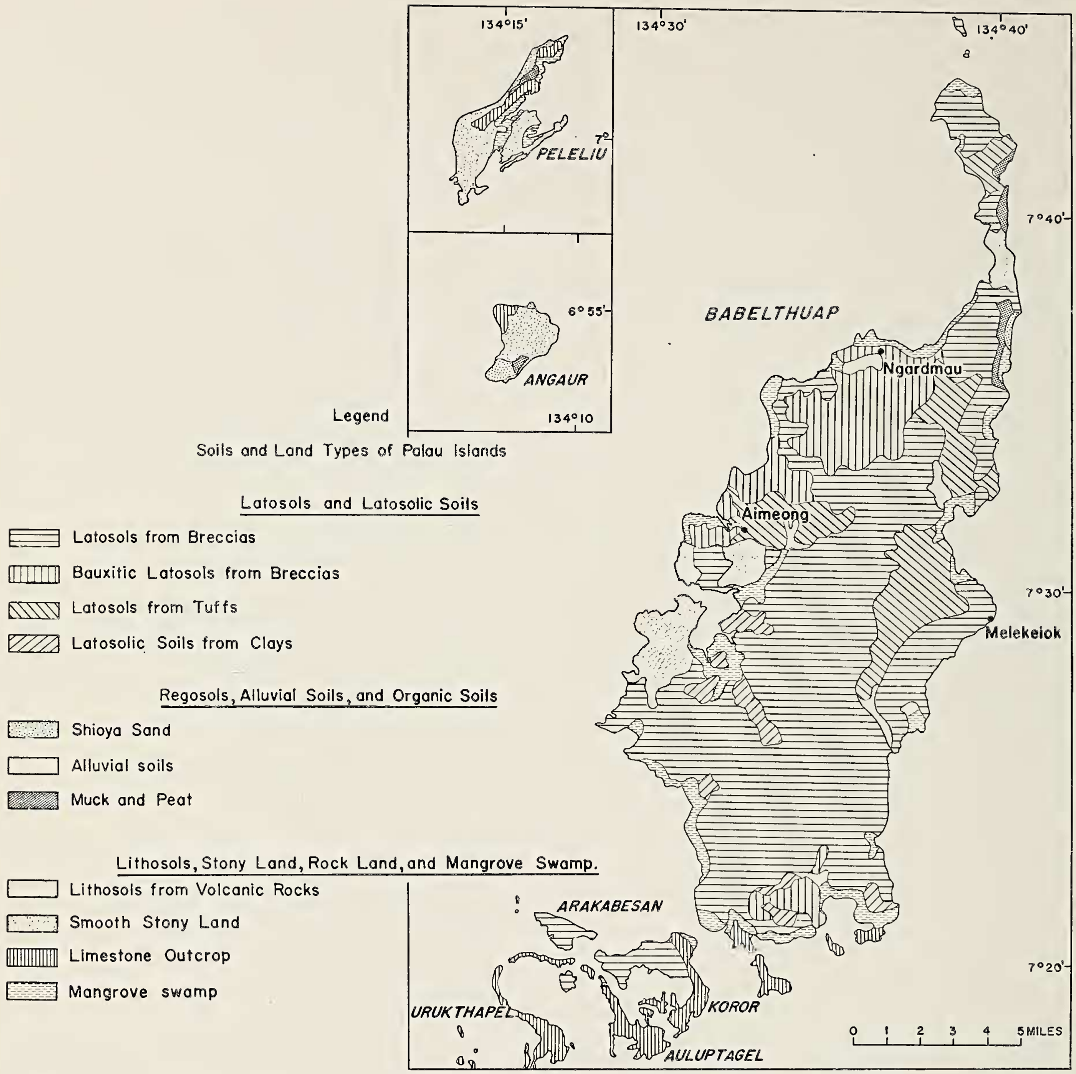

FIG. 2. Map showing the distribution of major soil associations and miscellaneous land types of the Palau Islands. High limestone islands and others that are not inhabited and consist of a single miscellaneous land type are not shown. Angaur and Peleliu, which are at the south end of the chain, are shown by inset maps.

laneous land types, with one exception—Shioya sand, a soil type.

Each soil association consists of one or more geographic areas with a restricted combination of soil types occurring together in a characteristic and repeating pattern. The individual soil types in each association have not been described and identified, however, as they would be in detailed surveys. The component soils in each association are classified into great soil groups or suborders.[4] Each association is then named for the dominant great soil group or suborder. The associations are described by listing the component soils

[4] The classification system followed in this paper is the one outlined by Baldwin, Kellogg, and Thorp (1938) as modified in a group of papers in *Soil Science*, Vol. 67, No. 2, February 1949, with two exceptions. The term and concept of "Latosol" as proposed by Kellogg (1949) are used. The term "Organic Soils" is used as a substitute for "Bog Soils."

and their approximate proportions. Patterns of occurrence of component soils also may be indicated. The component soils are described either by giving full morphological details for representative profiles together with data on topography and other features or by comparisons with soils that have been fully described.

Miscellaneous land types are geographic units without classifiable soils or with low proportions of such soils. Examples in the Palau Islands are smooth stony land and limestone outcrop. Stray patches of classifiable soils occur in each of these units but comprise a negligible portion of the total area.

The profile descriptions use horizon concepts and terminology as given in the *Soil Survey Manual* (Soil Survey Staff, 1951), unless otherwise stated. The identification of field textures, i.e., apparent texture as determined by the fingers when the profile was being described, is given for individual horizons. Pinholes refer to pores that are 1 mm. or less in diameter, whereas wormholes are tubular channels about 3 mm. in diameter. Numbers of pinholes, wormholes, roots, stone fragments, and concretions are indicated by three relative classes, viz., few, common, and many. Concretions are roughly spherical, unless otherwise noted, and their sizes are referred to the same limits as granular structure (see *Soil Survey Manual* for these size limits).

Each profile description is preceded by a brief statement on the geographic setting, and some are followed by comments not readily included in the description itself.

Latosols and Latosolic Soils

The Latosols are by far the most extensive soils in the Palau Islands, comprising some 60 per cent of the total land area. As shown by the map in Figure 2, they are dominant on Babelthuap, Koror, Arakabesan, and Malakal, and form the north tip of Auluptagel. Despite their large acreage, however, they have limited importance to local food production.

The Latosols of the Palaus are well drained, red to yellowish, friable, strongly acid, deep, and ferruginous or bauxitic soils derived mainly from volcanic rocks. The regoliths from volcanic rocks are weathered to great depths, but the soils do not seem to have correspondingly deep solums. The few latosolic soils formed from sedimentary clays are less deeply weathered and have shallower solums than do those derived from volcanic rocks.

These soils occur in moderately dissected uplands with a dendritic pattern of drainageways. Ridge crests are generally narrow, as are the valleys, and the intervening rounded slopes are relatively long. Local relief, i.e., differences in elevation within a unit area of approximately 160 acres (one-fourth square mile), are measurable in tens of feet, for the most part. In a few places local relief is measurable in one or two hundreds of feet, whereas in others it may be in feet.

Three associations are dominated by Latosols formed from volcanic rocks, whereas a fourth consists of latosolic soils derived from clays. Brief descriptive names are used to identify the major group in each association. Such names are not being suggested as proper names for great soil groups but are intended for local identification of the soils. When the name of an association is used as a subsection heading, it is followed by another name or names in parentheses. These names in parentheses identify the associations on the map of larger scale in the report on military geology of the islands (U. S. Department of the Army, 1956). The information on the larger map has been generalized in preparing the map in Figure 2.

1. Latosols from Breccias (Palau Association)

This association is dominated by Latosols that are red or reddish brown in the deeper profile. Colors are mainly of 2.5YR and 5YR hues[5] though a few soils are strong brown

[5] Munsell color notations. The application of this system of color notations to soils is discussed in the *Soil Survey Manual* (Soil Survey Staff, 1951).

(7.5YR hue) and a very few yellowish brown (10YR hue) below the A horizon. Bauxitic Latosols, Alluvial Soils, and Lithosols or lithosolic soils are minor components of the association. With a total area of 78 square miles, this association is much the largest in the Palau Islands. It extends from one end of Babelthuap to the other, covers all of Arakabesan and Malakal, and occupies those parts of Koror and Auluptagel underlain by volcanic rocks.

Topography is largely hilly; dominant slope gradients fall between 15 and 45 per cent. Departures from the dominant topography occur on major divides, where the uplands are undulating or gently rolling, and immediately adjacent to the valleys of large streams, where slopes are commonly steep. Hilly topography, however, dominates the association.

A profile description to illustrate the major reddish Latosols of the association follows.

(a) *Setting*. This profile was described and sampled on the island of Arakabesan about 1,000 yards west of the causeway leading to Koror. The site is about 100 feet above sea level in well-dissected uplands and has a slope of 15 per cent to the east. Vegetation in the vicinity has been disturbed by fire and by cutting, though there was little cultivation in evidence.

(b) *Profile Description.*

A_1	0-12″	Dark reddish-brown (5YR 3/4) silty clay loam, dark brown (7.5YR 3/4) when dry; weak, fine and very fine granular structure; soft, very friable; many roots; few stone fragments; strongly acid.
B_{21}	12-26″	Dark red (2.5YR 3/6) silty clay, yellowish red (5YR 4/6) when dry; compound structure of moderate fine and medium subangular blocks breaking readily to moderate fine and medium granules; slightly hard, friable, slightly plastic; roots common; few pinholes, wormholes, and stone fragments; strongly acid.
B_{22}	26-33″	Yellowish-red (5YR 4/6) silty clay, yellowish red (5YR 5/6) when dry; compound structure of moderate fine and medium angular blocks breaking readily to moderate medium and fine granules; slightly hard; friable, slightly plastic; few roots; pinholes and wormholes common; strongly acid.
B_{23}	33-39″	Comparable to B_{21} in texture, structure, and consistence but dark red (2.5YR 3/8) in color; few roots; pinholes and wormholes common; strongly acid.
C_1	39-60″	Brindled and finely variegated red, yellowish-red, pale-yellow, and light-gray (intermediate colors also present) silty clay loam; massive; soft, very friable; strongly acid.
C_2	60-102″	Similar to C_1 horizon but with lower proportions of grays in the color pattern.
C_3	102-120″	Finely variegated reddish-yellow and light-gray silty clay loam with few medium distinct mottles of weak red; massive in place but breaks out in weak coarse plates with black coatings on many faces; slightly hard, firm; strongly acid.

(c) *Additional Notes*. The identification of the B_{22} and B_{23} horizons is open to question. The B_{22} is like the adjacent ones in texture, structure, and consistence but not in color. The differences may reflect marked banding in the original parent materials or disturbance of some kind, possibly by man. Disturbance seems probable in view of widespread occurrence of pottery fragments at some depth in Latosol profiles in the Palau Islands. Laboratory data also suggest the possibility that the present B_{23} horizon may at one time have been an A horizon, later covered by soil material of similar composition moved downslope from higher uplands.

The slope gradient at the profile site on Arakabesan falls near the lower end of the dominant range for the association as a whole. Consequently, the solum is thicker than average. It is estimated that 10 per cent of the Latosols in this association have deeper solums and that 60 per cent have slightly shallower solums, i.e., between 2 and 3 feet. The remaining 30 per cent have solum thicknesses falling between 1 and 2 feet. Regardless of variations in solum thickness the regolith is deep for all Latosols in this association, commonly ranging from 10 to 60 feet. Occasionally, thickness of the regolith may exceed 60 feet to the underlying basaltic or andesitic volcanic Breccias.

Concretionary or bauxitic Latosols, Lithosols and lithosolic soils, and Alluvial Soils comprise from 10 to 15 per cent of the association. Proportions of these three minor groups are approximately equal. The concretionary Latosols are similar to the dominant soils in the association of bauxitic Latosols from Breccias. In contrast to the Latosols, the Lithosols and lithosolic soils are formed in shallow regoliths, usually marked by rock outcrops. The Alluvial Soils occupy toe slopes and narrow valleys and are similar to those described in the subsection on Regosols, Alluvial Soils, and Organic Soils.

2. Bauxitic Latosols from Breccias (Babelthuap Association)

The dominant soils of this association are the most strongly weathered Latosols of the islands. Striking features of these soils are the large numbers of concretions on the surface and in the profile. Approximately half of the total area of this association consists of reddish, bauxitic Latosols. Most of the remainder consists of Latosols that are low or lacking in concretions, but there are also minor proportions of Lithosols or lithosolic soils and of Alluvial Soils. Much less extensive than Latosols from Breccias, this association has a total of 19 square miles, all on Babelthuap. Major areas are in the west central part of the island, though two small ones are near the south coast.

Topography is dominantly hilly. Slopes may be slightly steeper, on the average, than they are in the association of Latosols from Breccias. Local relief is commonly measurable in many tens of feet.

A profile description representative of the dominant bauxitic Latosol of the association is as follows:

(a) *Setting*. The profile was described and sampled in a former strip mine used for the extraction of bauxitic ore, approximately 1,600 yards south of Ngardmau on Babelthuap. The site has a slope of about 15 per cent to the east. Vegetation near the strip mine consists of coarse grasses and brush interspersed with almost pure stands of ferns (*Gleichenia linearis*).

(b) *Profile Description*.

A_1	0-6″	Brown (7.5YR 4/4) gravelly loam; moderate fine granular structure; soft, friable; brownish coarse and very coarse vesicular platy concretions common, few brown fine concretions; many very fine, fine, and medium roots; few small worm casts; very strongly acid.
B_2	6-18″	Red (2.5YR 4/8) silty clay; compound structure of moderate coarse subangular blocks breaking

under pressure into moderate fine and medium subangular blocks; slightly hard, friable; brown fine concretions common; few fine roots; extremely acid.

C_1 18-28″ Variegated red (2.5YR 4/8), weak red (10R 4/3), and reddish-yellow (5YR 6/8) silty clay loam; massive; slightly hard, friable; few light-gray fine concretions, few fine roots; extremely acid.

C_2 28-32″ Variegated weak red (10R 4/3), reddish-yellow (5YR 6/8), and strong brown (7.5YR 5/6) silty clay loam; massive; slightly hard, friable; few brownish coarse and very coarse concretions; few speckles of gray (N 5/); extremely acid.

C_3 32-76″ Variegated weak red (10R 4/3) and strong brown (7.5YR 5/6) gritty silty clay loam, appearing mottled because of light-gray (10YR 7/1) fine to coarse concretions; yellowish-red very coarse concretions common; extremely acid.

C_4 76-96″ Variegated weak red, strong brown, and black silty clay loam; weak coarse platy structure apparently retained from parent volcanic breccia; very strongly acid.

(c) *Additional Notes.* The concretions in the A horizon are large and tend to be roughly platy, with long axes ranging from 5 to 100 mm. and short axes from 3 to 30 mm. All seem to be vesicular, and some have shiny surfaces. Concretions are most abundant in the surface layer and in the C horizon.

The nature and distribution of concretions in the profiles of dominant Latosols in this association tend to follow certain patterns. For the most part, brown, reddish-brown, and yellowish-red concretions occur in the surface layer, though they are found at depth in some profiles. Gray and light gray concretions occur in the C horizon, especially in the upper part. Colors suggest that concretions in the deeper profile are more often low in iron oxides than those near the surface. Most concretions in the upper horizons are somewhat flattened and platy, with a few being roughly spherical. In the deeper horizons, the concretions may be platy, spherical, or assume branching cylindrical forms much like reef coral. The spherical and platy forms are most common. Total numbers of concretions are greatest in the A and C horizons, and seem to be lowest in the B horizon. Numbers of concretions decrease with increasing depth in and below the C horizon, as a rule.

Sequences and thicknesses of horizons and the degree of horizonation are not uniform among the bauxitic Latosols and related soils dominant in this association. As already indicated, these soils comprise about half of the total area of the association. Perhaps 25 per cent of the soils in this half have the horizon sequence and thicknesses as described for the one profile. Other soils either have been eroded or have failed to reach the same degree of horizon differentiation. Most of the soils have thinner A horizons than the described profile, some lack an A horizon, and others seem to have lost both A and B horizons. Some of these last-named soils have thin A horizons which seem to be in process of formation from former C horizons. Thus, about three-fourths of the bauxitic Latosols and related soils in the association have profiles somewhat like but not identical with the one described near Ngardmau. Regardless of the character of the profile, the Regolith is consistently deep, commonly exceeding 30 feet and often reaching 50 feet.

Second in extent in the association are

Latosols formed from volcanic Breccias but lacking large numbers of concretions in the profile. These soils are identical with the dominant ones in the association of Latosols from Breccias, described earlier. Some do have more concretions in the surface layer than typical, thus being intermediate in character between the bauxitic and nonbauxitic Latosols.

Lithosols or lithosolic soils and Alluvial Soils comprise 10 per cent or less of the association. The nature and distribution of these minor soils is similar in the two associations of Latosols from volcanic Breccias.

3. Latosols from Tuffs (Ngardok Association)

Although derived from different parent materials, the dominant soils of this association closely resemble the Latosols formed from volcanic Breccias, especially those low in concretions. On the whole, the soils from tuffs have thinner solums and slightly lower permeability. They have fewer concretions in the profile and seem to be less weathered than the bauxitic Latosols from Breccias. Minor components of the association are Alluvial Soils and Regosols or regosolic soils. Total area of the association is 13 square miles, which is one-fifth that of the Latosols from Breccias. Latosols from Tuffs occur only on Babelthuap, mainly in the northern half of the island.

The land surface of this soil association is highly dissected. Topography is mostly hilly to steep with local relief in many tens of feet. Ridge crests are commonly narrow but valleys are fairly broad with much fill. Occasional uplands have been dissected so as to resemble miniature Badlands, which are conspicuous though small.

A profile description to represent the Latosols from Tuffs follows.

(a) *Setting*. The profile was described and sampled south of the village of Aimeong, west central Babelthuap. The site was a 25 per cent slope to the west in uplands about 100 feet above sea level and less than 100 yards from a mangrove swamp. The vegetation at the site consisted of coarse grasses and low shrubs.

(b) *Profile Description*.

A_1	0-3″	Reddish-brown (5YR 4/4) silty clay loam; weak medium granular structure; soft, friable; many fine and medium roots, few wormholes and pinholes; strongly acid.
B	3-18″	Yellowish-red (5YR 4/8) silty clay; weak coarse and medium subangular blocky structure; slightly hard, firm, slightly plastic, slightly sticky; many fine roots; few pinholes; strongly acid.
C_1	18-42″	Bedded deposit of weathered tuffs in which the main layers are variegated weak red (10R 4/2), red (10R 4/8), pale yellow (2.5Y 7/4), and white (2.5Y 7/2) silty clay loam that is soft and friable. Intercalated layers are reddish-yellow (7.5YR 6/6) silty clay that is hard, firm, slightly sticky, and slightly plastic. The whole horizon has weak, very coarse platy structure inherited from original deposit and is strongly acid.
C	42-60″	Variegated weak red (10Y 4/2) and pale-yellow (2.5Y 7/4) silt loam with very fine white (2.5Y 8/2) specks; massive; soft, very friable; strongly acid.

Major differences among the Latosols from Tuffs are in thickness and color of solum. Approximately half of these soils have solums 1½ or more feet thick. Another fourth have solums between 1 and 1½ feet in thickness.

The remainder have solums which are less than 1 foot thick. Colors range from low chromas and values of 10R hue to rather high figures of 7.5YR hue. The bulk of the soils have colors of 2.5YR and 5YR hues. Some profiles have appreciable numbers of concretions of various sizes in and on the surface layer. Concretions may be common but not numerous. Thickness of the Regolith in which the soils are formed is generally great, commonly falling between 40 and 100 feet.

Minor components of this association, the Alluvial Soils and Regosols or regosolic soils, form 10 to 15 per cent of its total area. The Alluvial Soils are similar to those in other associations dominated by Latosols. The Regosols or regosolic soils are restricted to the steepest slopes and have about the same total area as Alluvial Soils. The Regosols or regosolic soils may have faint A horizons or may consist entirely of weathered Tuffs.

4. Latosolic Soils from Clays (Ngatpang Association and Tabagaten Association)

Two soil groups are the main components of this association, all of which are derived from sedimentary clay beds. The more extensive group consists of Red-Yellow Podzolic soils which approach Planosols in fine texture and low permeability of the B horizon. They resemble the Colbert series formed from argillaceous limestones in the southeastern United States. The B horizons are mainly yellowish-brown (10YR hue) silty clays. The second major group in the association consists of yellowish-red to red soils which seem to be intermediate in character between Latosols and Red-Yellow Podzolic soils. They have some of the properties of each. They may be more nearly related to the Davidson, Decatur, and similar series than to typical Latosols or Red-Yellow Podzolic soils. All gradations in profile exist between the yellowish-brown and red components of this association.

Minor components of the association are Low Humic-Gley soils, Alluvial Soils, and Regosols, which collectively comprise about 20 per cent of its total area. Low Humic-Gley soils occur in smooth uplands and on the lower parts of long slopes. Alluvial Soils are found along drainageways. The Regosols occupy the rare steep slopes.

Restricted in its occurrence on Babelthuap, this association has a total area of about 5 square miles. The main bodies are in the west central part of the island, with a few small ones near the southern end.

Topography is dominantly undulating to rolling, in contrast to the hilliness of the Latosols from Breccias and Tuffs. Slopes are long and gentle. Local relief is measurable in feet as a rule though it may reach tens of feet in a few places. Latosolic soils from clays comprise the smoothest uplands on Babelthuap.

5. Chemical and Mineralogical Data on Profiles

Certain laboratory analyses have been made on samples of the major horizons of several profiles from the Palau Islands. Data obtained will be given in full in a later publication, but a few are given here to complement the morphological observations. Table 1 gives data for exchangeable cations, pH, exchange capacity, base saturation, and organic matter for three profiles which represent the dominant Latosols of the islands. Table 2 gives data on chemical and mineralogical composition on a section sampled for the study of bauxite ore in an area of bauxitic Latosols.

The laboratory analyses reported in Table 1 were made in the Department of Soils and Agricultural Chemistry, University of Hawaii, and in the Soil Survey Laboratories, SCS, U. S. Department of Agriculture. Methods used at the University of Hawaii are described by Piper (1944), whereas those used in the Soil Survey Laboratories are described in U. S. Department of Agriculture Circular 757 (Peech *et al.*, 1947).

Data given in Table 2 are from the laboratories of the U. S. Geological Survey. Standard methods for chemical analysis were used

TABLE 1
EXCHANGEABLE CALCIUM AND MAGNESIUM, pH, EXCHANGE CAPACITY, BASE SATURATION, AND ORGANIC MATTER IN THREE LATOSOL PROFILES

HORIZON	DEPTH	pH	CATION EXCH. CAPACITY	EXCHANGE-ABLE CALCIUM	EXCHANGE-ABLE MAGNESIUM	BASE SATURA-TION	ORGANIC MATTER
	Inches		m.e./100 g	m.e./100 g	m.e./100 g	Per cent	Per cent
LATOSOL FROM BRECCIA*							
A1	0–12	5.6	22.4	8.3	1.8	45	5.20
B21	12–26	5.6	15.3	6.2	0.8	46	2.35
B22	26–33	5.8	16.7	6.6	0.7	44	2.45
B23	33–39	6.2	20.3	7.8	0.5	41	1.44
C11	39–60	6.2	13.9	7.6	0.5	58	0.50
C12	60–88	6.6	15.8	8.8	0.7	60	0.37
BAUXITIC LATOSOL FROM BRECCIA*							
A1	0–6	5.0	12.0	0.4	0.4	6	4.79
B2	6–18	5.0	8.3	0.1	0.4	7	2.38
C1	18–28	5.2	10.1	0.3	0.5	4	0.98
C2	28–34	5.2	10.2	0.3	0.6	10	0.85
C3	34–76	5.2	14.3	0.2	0.3	4	0.64
LATOSOL FROM TUFFS†							
A	0–3		36.7	7.1	5.7	37	
B	3–18		31.0	12.2	2.8	50	
C1	18–42		31.5	19.6	1.8	69	
C2	42–60		30.7	17.6	1.7	64	

* Analyses through courtesy of Dr. G. D. Sherman, Chairman, Department of Soils and Agricultural Chemistry, University of Hawaii.
† Analyses by E. M. Roller, Soil Survey Laboratories, Soil Conservation Service, U. S. Dept. of Agriculture.

in determining composition of samples given in Table 2. The quantities of gibbsite and of silicate clay minerals were estimated by Goldich from differential thermal analyses and the chemical analyses. Hematite and other minerals were obtained by difference.

6. Comparisons of Soils in Palau Islands, Hawaii, and Puerto Rico

The Latosols in the Palaus have low degrees of horizonation, diffuse horizon boundaries, and common to numerous pinholes in the profile. Morphologically, they are comparable to Latosols observed by Simonson in Hawaii, Puerto Rico, Ceylon, and Brazil. There are differences, however, among the Latosols in the Palaus as there are elsewhere. The Latosols low or lacking in concretions seem to be much less strongly weathered than are the bauxitic Latosols high in concretions. This inference is based on differences in morphology and on laboratory data given in Tables 1 and 2.

The Latosols low or lacking in concretions have A horizons that are easily recognized because they are darker and more friable than the B and C horizons. The B horizons are set apart because they are more plastic and less friable than the C horizons. Differences in plasticity are slight as indicated by dominant ranges in plastic index values (Casagrande, 1932) of 6 to 9 for the A horizons, 21 to 31 for

TABLE 2
COMPOSITION OF LAYERS FROM A DEEP SECTION THROUGH A BAUXITIC LATOSOL FROM BRECCIA NEAR NGARDMAU, BABELTHUAP*

DEPTH	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	LOSS ON IGNITION	GIBBSITE	SILICATE CLAY MINERALS	HEMATITE AND OTHER MINERALS
Inches	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
0–20	0.98	44.12	25.55	1.38	26.14	66	2	32
20–28	1.64	34.83	37.56	1.68	21.76	51	4	45
28–120	7.63	37.33	29.85	1.70	21.22	47	17	36
120–180	19.40	35.21	24.62	1.42	18.75	29	42	29

* Sampled by S. S. Goldich; hole 17, Taihei Area. Chemical analysis by Marie L. Lindberg, U. S. Geological Survey.

the B horizons, and 6 to 18 for the C horizons. The C_1 horizon of the Latosol profile described on Arakabesan has a plastic index of 31, which is in the common range for B horizons.

Morphologically, the dominant Latosols in the Palaus are like the Humic Latosols in Hawaii, described by Cline (Cline *et al.*, 1939). The profiles from breccias and tuffs are much like the Humic Latosols in the character, sequence, and thickness of horizons. Both profiles in the Palaus, however, are lower in organic matter than Humic Latosols in Hawaii, being more like the Low Humic Latosols in this feature. The profile from tuffs has exchange capacities ranging from 31 to 37 milliequivalents per 100 grams which falls within the common range of 30 to 40 milliequivalents for Humic Latosols in Hawaii. On the other hand, the profile from breccia has exchange capacities ranging from 14 to 22 milliequivalents per 100 grams which parallels the range of 15 to 30 milliequivalents for Low Humic Latosols. Ratios of exchangeable calcium to magnesium are much higher in the two profiles from the Palaus than they are in the Humic Latosols or Low Humic Latosols of Hawaii. All in all, the less weathered Latosols of the Palau Islands seem marginal between the Low Humic Latosol and Humic Latosol groups recognized in the Hawaiian Islands.

The Latosols in the Palaus also resemble those in Hawaii in low plasticity and stickiness despite high clay contents. Some Low Humic Latosols in Hawaii are 80 per cent clay but feel as though they were silty clay loams when worked between the fingers. Field textures of Latosols in the Palaus seem marginal between silty clay loam and silt loam in the A_1 horizons and between silty clay and silty clay loam in the B horizons. There is little reason to believe that the Latosols of the Palaus are lower in clay than those in Hawaii.

Latosols, though high in clay, commonly have low shrinkage values upon drying and show little or no expansion upon wetting. This behavior has been correlated with high liquid limit and low plastic index values. The liquid limits for Latosols in the Palau Islands mostly range from 56 to 82. Lower values were found in the bauxitic Latosol, which had liquid limits of 39 in the A_1 and 45 in the lower C horizons. The plastic index ranges from 6 to 31, as was indicated in an earlier paragraph. Within the continental United States liquid limit and plastic index values of similar magnitude are found in the Davidson series (Fruhauf, 1946) and similar soils, which have been classified in the Reddish-Brown Lateritic group (Simonson, 1949). Although similar to Latosols in a number of ways, the Davidson profile has a much more distinct and far less friable B horizon. Field descriptions of the Latosols in the Palaus as well as the liquid limit and plastic index values suggest that these soils lean somewhat in their characteristics toward the Davidson series. Hence, they seem to be intermediate between modal profiles for the Latosol group and the Reddish-Brown Lateritic soils.

The morphology and composition of the bauxitic Latosols in the Palau Islands indicate that they are more strongly weathered than the Humic Latosols and more nearly comparable in this respect to the Humic Ferruginous Latosols of Hawaii. Sesquioxides have been concentrated to a high degree, partly in the form of concretions, in the bauxitic profiles (Table 2). Compared to the Haiku and Naiwa series in Hawaii (Cline *et al.*, 1939), the bauxitic profile is much lower in SiO_2 and TiO_2, somewhat lower in Fe_2O_3, and much higher in Al_2O_3. It is comparable in contents of SiO_2 and TiO_2, lower in Fe_2O_3, and higher in Al_2O_3 than the profiles of Nipe clay described by Marbut (1930). Thus the concentration of sesquioxides, considering both aluminum and iron, is comparable in the bauxitic Latosol to that of Humic Ferruginous Latosols of Hawaii and to the Laterite soils of Cuba and Puerto Rico. The chemical and mineralogical composition of the bauxitic profiles as indicated in Tables 1 and 2 suggests that it is one of the end products of soil formation in the humid tropics.

The Latosols of the Palau Islands clearly represent two subdivisions of the broad group or suborder. The bauxitic soils are examples of a strongly weathered group similar in many ways to the Nipe clay of Cuba and Puerto Rico and to the Humic Ferruginous Latosols of Hawaii. On the other hand, the profiles low or lacking in concretions in the Palau Islands resemble the Humic Latosols of Hawaii in some ways and the Low Humic Latosols in others. It may be that they should be considered comparable to Humic Latosols in the drier part of their climatic range. Dominant Latosols of the Palau Islands also seem to have a few properties in common with the Reddish-Brown Lateritic group of the southeastern United States.

Regosols, Alluvial Soils, and Organic Soils

These soils comprise about 6 per cent of the total land area of the Palaus but produce most of the food in the present agriculture. The one Regosol is a soil type widespread on Pacific islands, known as Shioya sand. The Alluvial Soils are moderately fine-textured and predominantly poorly drained, though they have a wide range in drainage conditions. Organic Soils consist of peats and mucks. The Alluvial Soils are slightly more extensive than either Shioya sand or the Organic Soils.

1. Shioya Sand

This soil type occupies raised beaches or low coastal terraces that are above wave action, principally in north Peleliu and at the north and south ends of Angaur. Additional areas too small to be shown in Figure 2 occur along the northeastern coast of Babelthuap and along the shores of Peleliu. Total area of Shioya sand in the islands is 2.7 square miles.

The profile of Shioya sand consists of a thin (2–3 inches) gray (2.5Y 5/1) or grayish brown (10YR 5/2) A_1 horizon over a light gray (2.5Y 7/2) C horizon. The whole profile consists of sand or fine sand, which may be replaced by gravel at depths of 2 to 4 feet. In most places, some coral fragments occur on the surface and throughout the profile. Consisting largely of coralline limestone fragments, Shioya sand is strongly calcareous.

Much of the total area of Shioya sand has been planted to coconut palms, for which the soil is well suited. Minor crops that seem to grow well are lemons, bananas, papayas, and breadfruit.

2. Alluvial Soils

These soils occur along most streams and along many of the upland drainageways in the Palau Islands. Only the areas along the lower courses of principal streams can be shown, however, in Figure 2. The soils are all slightly acid in reaction, and the dominant ones are poorly drained. Less extensive are the well-drained soils and those intermediate in drainage. Total area of this association is slightly more than 4 square miles.

The dominant poorly-drained soils show the effects of a water table at or near the surface an important part of each year. A typical profile has a surface layer of brown (7.5YR 4/4) silty clay loam about 9 inches thick underlain by gray (5Y 5/1) or olive-gray (5Y 4/2) silty clay mottled with brownish yellow (10YR 6/8). Somewhere between 2½ and 4 feet this gives way to dark-gray, nearly impermeable clay free of mottles.

Well-drained soils in this association are commonly of similar texture but have brown surface layers grading downward into red, reddish brown, yellowish red, or yellowish brown. Mottled patterns and colors of 5Y hue are lacking in the well-drained soils. Soils with drainage intermediate between the well-drained and poorly drained ones are also intermediate in their morphology.

The Alluvial Soils are adapted to most crops that can be grown in the Palau Islands. In spite of the suitability of the soils for cultivation, however, very little of this association was being tilled in 1948. Most areas were idle, generally supporting tall coarse grasses which were replaced locally by poor forest. Taro was being grown on some patches of wet Alluvial Soils near villages. Other crops that seem to grow well on the Alluvial Soils are cassava, bananas, coconuts, and pineapples.

3. Muck and Peat

These organic soils are of major importance to present food production, despite their small total area. They occur as scattered individual bodies, mostly along the northeast coast of Babelthuap and on the islands of Angaur and Peleliu. Some bodies are too small to be shown in Figure 2. The total area of organic soils is slightly less than 3 square miles.

Muck consists of black, neutral to mildly alkaline, highly decomposed organic matter mixed with some mineral matter. Thickness of the muck commonly ranges from 2 to 3½ feet although it may be slightly less than 1 foot thick in places. The muck is generally underlain by gray silt, gray clay, or coral sand. On Angaur, all of the muck is underlain by phosphate ore in the form of pellets. Approximately 90 per cent of the total area of organic soils consists of muck.

Peat is less decayed than muck and is also commonly lower in mineral matter. Plant structures in the peat can be readily identified. The deposits range from 1 to 3½ feet in thickness over limestone or phosphate ore. The areas of peat are approximately 10 per cent of the total of Organic Soils.

The Organic Soils are especially valuable in the Palau Islands because of their suitability for taro production. They produce high yields of the crop, which is a major item in the diet of the people.

Lithosols, Stony Land, Rock Land, and Mangrove Swamp

This group comprises one soil association and three miscellaneous land types. Collectively, the group has a total area of 49 square miles, ranking second to the Latosols from Breccias. Despite their large extent, however, the Lithosols and miscellaneous land types have little usefulness to agriculture.

1. Lithosols from Volcanic Rocks

The main features of this association are the shallowness of soils, common occurrence of rock outcrops, and steep topography. Usually 6 to 15 inches deep over hard rock, the soil is dark, slightly acid, and commonly marked by a faint and thin A_1 horizon. Rock fragments are common on the surface and throughout the profile. Massive rock outcrops occur along ridge crests. The association has steep to hilly topography and is covered by forest or savanna. The steepest areas are mostly in forest, whereas the remainder is covered by coarse grasses and low shrubs with scattered pandanus trees. Restricted to Babelthuap and small nearby islands not shown in Figure 2, this association has a total area of 7 square miles.

2. Smooth Stony Land

Smooth stony land is largely covered by limestone fragments or rubble, among which are small quantities of fine earth, usually phosphatic. For the most part, large limestone fragments are numerous enough on the surface so that a person can easily step from stone to stone. Pockets of soil material are commonly tiny but a few are as big as 1/100th of an acre. The soil material is dark brown, friable, silt loam to loamy coarse sand and may reach depths of 10 inches in some pockets. As the name of the land type suggests, smooth stony land is nearly level or very gently sloping. It forms important parts of Angaur and Peleliu and has a total area of 2½ square miles.

Most areas of smooth stony land are covered by brush and small trees. Small clearings, usually a fraction of an acre in size, are made here and there in the forest for the planting of cassava, sweet potatoes, bananas, and papayas. These may be planted separately or in mixtures, more often the latter. Individual clearings are usually abandoned to the forest again after a few crops have been produced.

3. Limestone Outcrops

This form of rock land, as its name suggests, comprises exposures of coralline limestone and rubble with little or no fine earth. The surface of the limestone is commonly pitted and pinnacled. Some soil material is present in small pockets and in crevices, generally in handfuls. Present vegetation consists of small trees and shrubs. Limestone outcrop forms the islands of Urukthapel, Eil Malk, and Ngergoe (all of which lie between Koror and Peleliu and are not shown in Figure 2); parts of Anguar, Auluptagel, Koror, and Peleliu; and the southern tip of Babelthuap. It also forms a number of small unnamed islands between Koror and Peleliu. This land type has a total area of 24 square miles, none of which is inhabited.

4. Mangrove Swamp

This miscellaneous land type comprises wooded coastal areas that are periodically flooded by salt or brackish water because of tides. The mangrove swamps occur along the coasts, on deltas, in embayments, and along the lower reaches of the streams. The main areas border the coast of Babelthuap and the eastern coast of Peleliu. Total area of mangrove swamp in the Palau Islands is slightly more than 14 square miles.

AGRICULTURE

Agricultural production in the Palau Islands in 1948 was of a subsistence type. The crops being grown were used as food for the families producing them. The main food crops were taro, cassava, and sweet potatoes. Production of these crops was by hand tillage, a clear index to the prevailing level of agricultural technology.

Crops

Taro (*Colocasia esculenta*), which yields an edible tuber, is produced mainly on Organic Soils and poorly-drained Alluvial Soils in the Palaus. It is also grown to a limited extent on Latosols, preferably on lower slopes where some seepage can be expected. Commonly grown with taro but on the outer margin of the paddies is a coarser plant (*Cyrtosperma chamissonis*) which produces a large tuber eaten when the taro crop fails. Several large "elephant ear" varieties, identified by Fosberg[6] as *Xanthosoma violacea* and *Alocasia macrorrhiza*, are grown occasionally on soils of the uplands. Like the *Cyrtosperma* in the paddies, these are also eaten only during severe food shortages.

The second crop of importance is cassava (*Manihot utilissima*), called "tapico" by the Palauans. It commonly supplements and may replace taro in the diet. The crop was introduced during German ownership of the is-

[6] Personal communication, April 9, 1951.

lands. Improved varieties with higher starch contents were brought in by the Japanese who raised cassava for export. The crop grows best during the driest season of the year, when fungus diseases are the least active. It is grown mainly on the Latosols but to some extent on Alluvial Soils.

Third in importance among food crops are sweet potatoes, which were introduced by the Spaniards. Sweet potatoes are produced by the same methods as cassava. They are grown on the Latosols, some Alluvial Soils, and Shioya sand.

Minor crops are coconuts, sugar cane, Tahitian chestnuts, breadfruit, jakfruit, pineapples, oranges, mangoes, papayas, sauersop, and pandanus. Coconut plantations were relatively important at one time but the invasion of the rhinoceros beetle has reduced production to very low levels and forced abandonment of most groves. Sugar cane, pineapples, and papayas are grown as scattered plants in a patch of cassava, sweet potatoes, or both. Orange and mango trees producing food are commonly lone plants in or near the villages, whereas chestnuts, breadfruit, jakfruit, sauersop, and pandanus grow wild in the savannas and forests.

Methods

Shifting cultivation is the general practice in the production of food crops on the Latosols of the Palau Islands. Most areas of Latosols readily accessible to villages are now in savanna vegetation. Burning of the grass is therefore the first step in clearing a garden patch. A few areas of Latosols as well as most of the smooth stony land is in forest or brush. Clearing of a garden then requires the cutting of saplings, vines, and brush, usually done with a large knife or machete. After the savanna is burned or the forest cut, the soil is stirred with a simple hoe and crops are planted.

All tillage, planting, and harvesting in the Palau Islands are done by hand. No draft animals were on the islands in 1948 nor had they been used in the past. Cultivation of the soil is by means of a four-pronged hoe introduced by the Japanese. Tillage consists of stirring of the soil to shallow depths. Subsequently, slips or seeds are planted. Vegetative reproduction by means of slips is the more common practice.

Garden patches on Latosols and some on Alluvial Soils and smooth stony land are usually planted to cassava or sweet potatoes. Some gardens may have both crops growing at the same time, plus scattered individual plants of other crop species. A single garden may be used for cassava or sweet potatoes exclusively, or the two may be alternated. After the plants become ripe they are harvested a few at a time, as needed by the family. The patch is replanted with cassava or sweet potatoes after all of one crop has been harvested. This process is then repeated until yields in that one garden patch begin to drop. Once the yields have fallen, the patch is abandoned and a new one is cleared either by fire or knife. The whole process is then repeated once more in the new clearing.

Continuous growing of taro is common practice on the Organic Soils and the poorly drained Alluvial Soils. The planting, weeding, and harvesting of taro are the responsibility of the women in the families, who also own the taro paddies. The paddies used by a single family are divided into a number of segments and planted so that one segment is always ready for harvest. Thus, the plants in different segments of one paddy may be in all stages of growth from slips that have just been placed into the soil to ripe plants awaiting harvest. After all of the plants in a given segment have been harvested, that segment is again replanted while harvest begins in another part of the paddy. Taro paddies commonly receive more attention than do upland gardens because of their greater importance in food production.

Efforts are made by the Palauans to incorporate decayed leaves and grass as well as wood ashes into the soils, especially in taro paddies. Commercial fertilizers, insecticides, and the like, have not been available in the Palau Islands. Methods used by the Palauans to maintain and improve their soils as well as methods of tillage, planting, and harvesting are all common elements of a simple agricultural technology.

Potentialities

Improvements in agricultural technology would permit increased food production from the soils of the Palau Islands. Some improvements are possible within existing patterns of operation. For example, better crop varieties, commercial fertilizers and insecticides, and simple machinery such as hand cultivators could be used in the present agriculture. Certain shifts are thus possible without major changes in the agricultural arts. Such shifts would mean appreciable increases in food production, without realization of the full potentials of the soils.

To achieve full potential production from soils of the Palaus, major changes from the present agricultural technology would be required. What the potential may be can be inferred from current yields on Humic Latosols and Low Humic Latosols of Hawaii, soils which are comparable to those of the Palau Islands. Yields of 8 to 10 tons of sugar per acre are common on the Latosols of Hawaii (Cline *et al.*, 1939), where soil management includes heavy fertilization, irrigation, mechanization, and many more of the management elements available to agriculture in a modern industrial society. The findings of modern science and the products of modern industry are widely used for crop production on Latosols in Hawaii. Thus, the level of agricultural technology is markedly different from the one prevailing in the Palau Islands.

Experience in soil use and management does not seem directly transferable from Hawaii to the Palaus, though major soils in the two island groups are the same. The total land area and the topography of the Palaus impose certain limitations on agricultural production even with the best technology available. The small total area of the Palaus in itself restricts opportunities for the large scale agriculture in which sugar cane, cacao, and similar crops are commonly produced. Furthermore, the major soil associations of the Palau Islands are dominantly hilly to steep. Individual areas with level, undulating, or rolling topography are small. Proportions of the major soil associations with topography favorable for mechanization are therefore small. As a consequence, full use of the tools of soil management available in a modern industrial society does not promise to become feasible in the Palaus. Something less than full use of those tools is more likely to be appropriate. Possibilities for commercial agricultural production seem limited, all in all, but there is opportunity for greater food production through improvements in soil use and management.

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